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Issues and solution approaches in PHEV integration to smart grid

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ABSTRACT

Successful integration of plug-in hybrid electric vehicles (PHEVs) into the power system is a major challenge for the future smart grid. As a result, this topic has attracted the attention of researchers from different communities in the past few years. Recent research progress has addressed different technical aspects of PHEV integration into the smart grid; such as charging and control strategies of PHEVs, vehicle-to-grid (V2G) technology, and several application domains, such as wind energy integration, frequency regulation, design of parking areas and participation in electricity markets. Most of these works require formulation of mathematical models which extensively use artificial intelligence techniques, intelligent methods and agent-based computing approaches to solve the computational problems. This paper presents a comprehensive survey of different research problems and their solution approaches in the context of PHEV integration to smart grid.

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1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are gaining recognition as a cleaner alternative to fossil fuel vehicles. Economic viability of PHEVs, such as Toyota Prius, Chevrolet Volt and other electric vehicles are likely to pave the way for their large scale adaptation in smart grid in the near future. The higher penetration of PHEVs not only makes the transportation sector less carbon intensive, but also likely to play a significant role in improving the overall efficiency of power system by playing an active role in demand side management, spinning reserve services and reducing the uncertainty of renewable energy generation. However, it will create significant new load on the distribution network, and their charging and usage is critical for the distribution grid thereby making the integration of PHEVs into the electric grid much more challenging. The promising concept of vehicle-to-grid (V2G) [1,2], which conceptually allows bi-directional power flow between the vehicle and the grid further adds to the problem complexity and scalability for a modern power system. In this paper, different research problems are identified and the corresponding literature is comprehensively surveyed to bring together various issues and solution techniques.

1.1. Related work

There have been recent survey articles in the literature in the subject of PHEV integration to smart grid. Previous review works have focused on specific aspects of PHEV research. In this subsection, we focus on these survey articles and give an overview of the topics covered by them. With higher usage of PHEVs in the society, the distribution grid will be subject to greater stress due to surge in electricity demand for charging requirements of PHEVs. The impact of charging of PHEVs on distribution grid is typically analyzed in terms of voltage deviations and power losses by studying driving patterns, vehicle penetration and charging characteristic. Refs. [3,4] give comprehensive overviews of the related research. On the basis of the availability, reliability and value of vehicle-provided ancillary services, the direct deterministic vehicle command architecture is compared with aggregative vehicle command architecture in [5] to develop a feasible and economically viable V2G infrastructure. In a related topic, effectiveness of different communication architectures in the smart grid is surveyed in [6]. Different plug-in and V2G capable vehicles along with their power electronics topologies are reviewed in [7]. A review of energy storage, generation and control systems is carried out in [8]. A bibliographic survey on the role of the aggregator in the power system operation and electricity market is provided in [9]. Economic implications of charging the vehicle or sending back the power to grid are briefly discussed. A short review of economic dispatch in presence of PHEVs is given in [10]. Faria et al. [11] survey the environmental impacts, such as greenhouse gas emission reductions, of PHEVs. In a recent work [12], the authors survey the trends in the market of PHEVs. Their focus is on agent-based, consumer choice and time series based methods. Impact of PHEVs on distribution network, communication requirements, charging infrastructures, surveys on battery technology is surveyed in [13]. Apart from technical challenges, social acceptance of PHEVs and other renewable energy resources in the smart grid is an important factor for the eventual success of these technologies. Several factors that act as social, cultural and institutional barriers to the acceptance of cleaner alternative to energy are discussed in [14] and [15].

1.2. Contributions of the paper

In the present work, our focus mostly lies on different control and optimization problems and the computational tools employed to solve them. Smart grid technologies typically require algorithms and mechanisms that can solve problems involving a large number of highly heterogeneous actors, each with their own aims and objectives, having to operate within significant levels of uncertainty and dynamism. New challenges for research in artificial intelligence (AI) provided by the smart grid are discussed in [16]. We review on four different aspects of PHEV integration into the smart grid. We give a very short summary of each of them and their connections to the recent literature here.

1. Charging and scheduling of PHEVs
   PHEVs have an onboard storage device which needs charging for driving requirements. This creates additional demand on the power grid. If PHEV owners charge their batteries in an uncoordinated fashion, it runs the risk of increasing the peak load, which is both costly and has adverse environmental effects. On the flip side, coordinated charging can aid in reducing peak load and providing ancillary services. Smart charging strategies can be classified broadly into centralized and decentralized ones, and discussing different proposed methods is a focus of this survey. While there have been previous short review articles on this topic, such as [17], our survey is more broad and covers a wide variety of topics, such as vehicle-to-grid, online and agent based models, and battery life cycle optimization.
2. Applications in renewable energy integration
   Integration of renewable energy is another challenge for the future smart grid. Renewable energy production, such as wind and solar photovoltaic, depends significantly on factors such as weather. Therefore, the energy produced by those sources tends to be intermittent and widely fluctuating in short time. Introducing such uncertain power sources to the grid requires power reserves of higher magnitude. The energy storage systems in PHEVs can play a significant role in reducing the fluctuations in renewable energy generation by being a controllable source and sink of power. Recent review articles have surveyed various technical issues of renewable energy integration [18]. Richardson [19] studies the role of PHEVs in integration of wind, solar and biomass energy. In this paper, the focus of the survey is on the algorithmic and computational tools used in the literature for this problem. Several case studies on implementation projects using PHEVs for wind energy integration are presented, and so are some recent innovative ideas.
3. PHEV participation in electricity markets
   Charging (and discharging in the V2G mode) of PHEVs require interaction with the electricity market. While each individual PHEV handles less quantity of power, the aggregate amount of power exchanged between the grid and the PHEVs is significant. Therefore, an aggregator agent is envisioned for the PHEVs, similar to the load serving entities for the residential consumers. We focus on different aspects of this interaction with the grid, such as aggregator bidding strategies, unit commitment problems and so on.
4. Infrastructure and smart parking
   Higher penetration of PHEVs require adequate support infrastructure and smart parking facilities. Some prior survey articles in this area have been published. The infrastructure requirements for PHEVs in single family residential, multi-family residential and commercial stations are analyzed in [20]. Costs associated with this infrastructure are tabulated, providing an estimate of the infrastructure costs associated with PHEV deployment. Ralston and Nigro [21] have presented literature review on PHEVs with a focus on issues and solutions related to vehicle deployment and integration with the United States electrical grid and various subjects like vehicles, electricity, passenger vehicle market, public policy are discussed. It also provides a foundation for the way to overcome some of the major hurdles in present

and future PHEV deployment in the United States. Electric vehicle charging infrastructure in Poland is reviewed in [22]. The scope of the present paper in the context of infrastructure and parking area requirements is very different from the above references. We focus on the design strategies of smart parking areas, and different smart charging and scheduling strategies of PHEVs in them.

These study aspects are listed in Table 1 with major issues and related references. While critical to the success of PHEVs in the smart grid, many of these problems are relatively less explored in the existing review literature. Review on each aspect includes related research problems and proposed solution algorithm with their merits and demerits. One of the main themes of the paper is to contrast between centralized, decentralized and agent-based solution approaches studied in the literature. To give a basic overview of their modeling differences, we cite Figs. 1 and 2 from the cited references.

2. Charging and scheduling of PHEVs

2.1. Unidirectional operation

In the unidirectional mode of operation, PHEVs act as a flexible load interacting with the grid while charging their batteries. Charging strategies must be smart, that is charging of the PHEVs in the grid must be coordinated to prevent increase of peak load, reduce uncertainty in renewable energy generation, and so on. Therefore it is important to coordinate the charging of PHEVs taking the global grid conditions into account. Suitable coordination strategies of PHEV charging are explored in the literature. A real-time smart load management (RT-SLM) algorithm is proposed and developed in [23] for the coordination of PHEV charging on real time basis, with the objective being minimization of total cost of the energy generation and the associated grid energy losses. Simulation results for uncoordinated and coordinated charging at different PHEV penetration levels under three designated time zones for different charging scenarios are performed. Based on quadratic programming, smart energy control strategies are proposed in [24] for charging of PHEVs to minimize the peak load and flatten the overall load profile. Two control strategies, local energy control strategy and iterative global energy control strategy are proposed. Results show that both control strategies improve the flatness of the load profile, but global energy strategy is superior to the local energy control strategy. To minimize the power losses and to maximize the main grid load factor, a coordinated charging method is proposed in [25] to optimally schedule the PHEVs. Shortcomings of uncoordinated charging are discussed. IEEE 34 node test feeder is used as radial network for experimental purposes.

In the context of coordinated charging, the relationship between feeder losses, load factor and load variance is explored in [26]. Three optimal charging algorithms, with the objectives being, loss minimization, load factor maximization and load variance minimization are developed using these relationships to optimize the impact of PHEVs on connected distribution system. The additional benefits of reduced computation time and problem complexity on using load factor or load variance as objective function rather than system losses are also illustrated. The basic functions of an electric vehicle charging provider are described in [27] with a focus on associated optimization problems. A novel method for charging the electric drive vehicles is proposed including grid constraints on both power and voltage and tested in a simulated environment based on the Danish Island power grid. A distributed charging method for PHEVs where users can adopt charging rates according to their preferences is proposed in [28]. The authors use a type of congestion pricing and show that pricing information is very useful to regulate the user demand and balance the network load. Results show that the burden of load leveling can be shifted from the grid to the end users via suitable pricing.

2.2. Vehicle-to-grid

In the V2G mode, both charging and discharging to the grid need to be controlled for cost effective operations of the PHEVs. The related literature focuses extensively on different intelligent strategies for optimal charging and scheduling of PHEVs. To maximize the profits from grid transactions based on electricity pricing, the output power levels and charge/discharge times are scheduled intelligently in [29] and effects of grid faults on V2G are also presented. Binary Particle Swarm Optimization (BPSO) technique is used to schedule

Table 1
Phev integration to smart grid.

Sl. no	Study aspects	Operation modes/control objectives/major issues	References
1.	Charging and Scheduling of PHEVs	(a) Unidirectional charging methods in optimization based frameworks and real time intelligent algorithms	[23–28]
		(b) V2G mode, both charging and discharging control using various deterministic, and heuristic optimization techniques	[29–43]
		(c) Charging control in the grid	[44–49]
		(d) Online mechanisms for coordinated charging and game theoretic models	[50–53]
		(e) Optimal battery charging operation	[54–56]
2.	Application in reducing intermittence of renewable energy production	(a) Suitable control strategies of PHEVs for integration of wind and other intermittent renewable energy resources	[57–60, 72–75]
		(b) V2G mode of operation of PHEVs for renewable energy integration	[61–69]
		(c) Unconventional approaches	[76–79, 70–71]
3.	PHEV participation in Electricity Markets	(a) Multi-agent based, game theoretic models for PHEV participation in electricity market	[80–87]
		(b) Optimization-based methods	[88–94]
		(c) The customer perspective regarding the PHEV market and its participation	[95–96]
		(d) V2G mode of operation	[97–101]
		(e) Scheduling of PHEVs within a parking station and optimal charging/discharging rate determination	[102–106]
4.	Infrastructure facilities and Energy management schemes	(a) Estimation of availability of PHEVs for charging	[107–109]
		(c) Parking areas functionality as power sinks or power source, charging station requirements	[110–117]

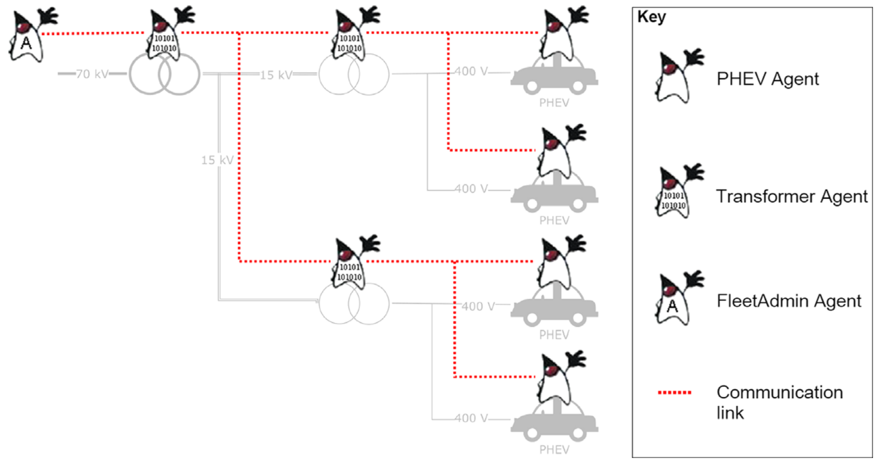

Fig. 1. An agent-based charging scheme [69].

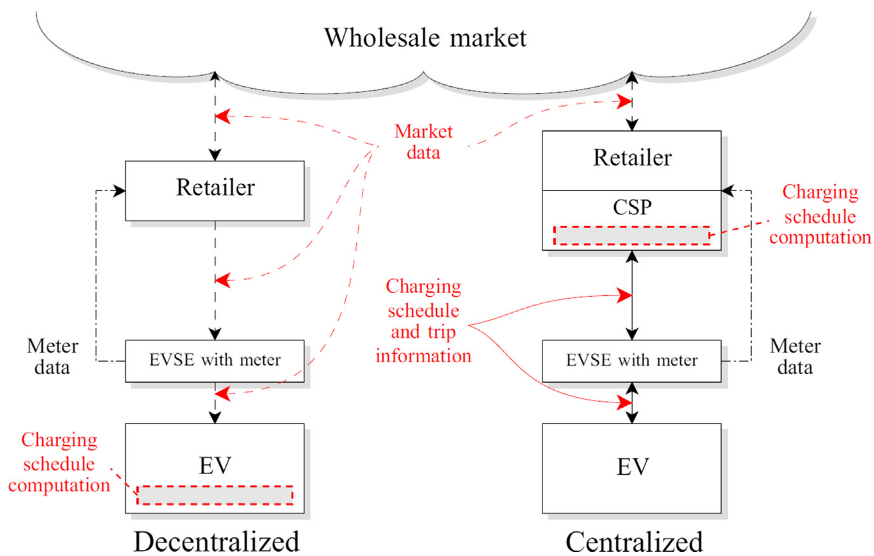

Fig. 2. Comparison of centralized and decentralized operation of PHEVs in an electricity market [85].

the vehicles, and results show that advanced control and protection is needed to avoid any adverse effects caused by the large bidirectional power surges to the batteries and the inverters of the individual plug in vehicles. An approach to optimize the electric charge behavior with the goal of minimizing the charging costs, achieving satisfactory state of energy levels and optimal power balance is described in [30]. Results show linear programming is sufficient in considering electric vehicle charging optimization. An optimal control strategy based on discrete Particle Swarm Optimization (DPSO) is presented in [31] to determine appropriate charge and discharge times for fleet of vehicles for a given load curve. The constraints are decided by battery characteristics and as set by vehicle owner. Results show that V2G power capacity does improve the load curve under the proposed technique.

An optimal PHEV charging and discharging scheduling scheme is assessed in [32] to achieve peak shelving and reduction of variability of the load of households connected to a local distribution grid. Results show that even in the absence of V2G, a local control strategy significantly reduces peak load as compared to uncontrolled charging. The voltage deviations are reduced significantly by this charging strategy. A hierarchical framework for managing the controllable load in the large power system to build a multilayer control structure is proposed in [33]. To minimize the power loss an optimal algorithm is derived for charging and discharging of PHEVs. Constraints due to charging rate, battery state and power system operation limits are incorporated. Simulation results show that the proposed optimal charging scheme can reduce voltage deviation below 10% of distribution nominal voltage and also minimizes the power loss.

Two algorithms based on forecast of future electricity prices are proposed in [34] using dynamic programming to find economically optimal solution for vehicle owner. The first optimizes the charging time and energy flow and reduces the electricity cost substantially without increasing battery degradation. The second takes into account V2G support as means of generating profits. Experimental results based on California Independent System Operator (ISO) data indicate that smart charging reduces electricity cost of driving from \$0.43 to \$0.2 and provision of regulating power results in a daily profit amounting to \$1.71 including cost of driving.

A V2G algorithm is developed in [35] to optimally schedule the energy and ancillary services in order to maximize the profit to aggregators while providing flexibility and peak load shaving to the utility and low costs of vehicle charging. Driving profiles are constructed using data from 2009 National Highway Travel Survey for urban Texas households. Results show that algorithm offers significant financial benefits to the consumers and aggregators for different battery replacement costs providing additional system

flexibility as well as peak load reductions. A real time current controlled PHEV parking lot is presented in [36] and the controller is designed in such a way that the transaction of both active and reactive power with grid can be controlled independently and the current going out of the vehicle during the faults is limited for better protection. The control is modified so that the parking lots can function in voltage control mode by injecting required amount of reactive power.

A BPSO technique is used in [37] to schedule the vehicles when to buy or sell the power to achieve maximum profits under both single and multiple transaction conditions per day. Price curves from California Independent System Operator (ISO) database are used and multiple transactions in a day resulted in much higher profits. Results are compared for scalability and consistency. An algorithm for unidirectional regulation and profit maximization considering operational system load and price constraints is developed in [38] for an aggregator. The optimal analogues of three charging techniques are developed. The developed algorithms are simulated on a hypothetical group of commuter cars in Pacific North West using regional transport and show that each algorithm offers benefits to different participants but only optimized algorithms provide significant benefits to all participants.

A real time V2G control problem with price uncertainty is studied in [39]. The electricity price is modeled as a Markov chain with unknown transition probabilities and formulated the problem as a Markov decision process. A Q-learning algorithm is used to adopt the control operation to the hourly available price in order to maximize the profit for the vehicle owner during the whole parking time. The proposed algorithm is evaluated using both simulated price and the actual price and shows that the proposed algorithm can work effectively in real electricity market and able to increase the profit significantly compared with conventional charging scheme. A PSO algorithm is proposed in [40] to solve optimal scheduling considering the point of view of an aggregator using different resources, with emphasis on distribution generation and V2G. The impact of PHEVs on the power quality of smart grid distribution systems for different battery charging rates are studied in [41]. Impacts of PHEV charging rate on voltage profile, fundamental and harmonic losses, transformer loading and total harmonic distortions are studied. It is illustrated in results that with low PHEV penetration, harmonic levels and voltage deviations are acceptably low with the least amount of losses at normal charging rates. Moreover, when quick charging rate is considered, significant voltage harmonics and losses with transformer overloading occurs if charging is concentrated at peak times. However, high PHEV penetrations cause unacceptable and severe voltage harmonics, deviations, power losses and transformer overloading.

A typical distribution system of a large city is modeled to demonstrate the V2G capabilities such as meeting peak demand and voltage reduction in [42]. Simulation study of distribution system with charging station controller and V2G controller using fuzzy logic shows the easy control of charging and discharging, flattening of load profile and improvement in voltage stability. Use of intelligent solutions for monitoring and controlling the electrical grid when connected to PHEV batteries is demonstrated in [43]. Two intelligent controllers, fuzzy load controller and fuzzy voltage controller are designed for V2G to supply peak power, balancing control, load leveling and voltage regulation. Results show intelligent controllers can achieve balance of the generated power and load while controlling average voltage, power losses and efficiency of the grid.

2.3. Charging control in the grid

The scheduling problem for PHEV charging is augmented into the Optimal Power Flow (OPF) model to obtain a joint OPF-charging (dynamic) optimization in [44]. A solution to this highly non-convex optimization formulation maximizes the network performance by minimizing the generation and charging costs in IEEE 14 bus system while satisfying the network, physical and inelastic load constraints. Moreover, this optimization algorithm can be easily generalized to more complicated joint OPF-charging problems with additional constraints. A detailed framework of a Time Coordinated Optimal Power Flow (TCOPF) tool to illustrate the trade-offs that distribution network operators might encounter when implementing various load control approaches of electric vehicles (EV) is presented in [45]. A case study with in United Kingdom context show that the electrical infrastructure could easily cope up with the additional load of EVs. It also highlights that the current cost given to emissions at the exchange market is insufficient to drive EV load control strategies compared to spot prices of electricity. Based on randomized EV charging start times and simple one way broadcast communication allowing for a time delay between communication events a control algorithm is developed in [46]. Using arguments from queuing theory and statistical analysis, the authors seek to maximize the utilization of excess distribution capacity with a minimal probability of overloading the circuit.

The problem of allocation of EV rechargers in urban areas was investigated in [47] for Musashino city. A priority order among energy station candidates is defined by comparing with a Voronoi diagram and the priority order circular diagram. The use of this approach leads to obtaining a blue print for establishing the infrastructure required to support future traffic of electric vehicles as well as providing guidelines and knowledge on strategic energy provision services for utility companies. A solution for integrating electric vehicles in the smart grid through unbundled smart metering and Virtual Power Plant (VPP) technology dealing with multiple objectives is presented in [48]. In this framework, EV can provide the benefit of cost effective energy during the charging and also provide multiple ancillary services to the network. A new multilayer framework is developed in [49] to implement the concept of V2G. Simulation results shows that both operation and emissions cost are minimized using PSO algorithm when both cost and emissions are considered in the fitness function.

2.4. Online mechanisms and game theoretic models

A novel online allocation mechanism is proposed in [50] for PHEV charging to be coordinated in order to accommodate the capacity constraints. The authors proposed a model-free online mechanism with perishable goods to handle multi-unit demand with decreasing marginal valuations. Empirical evaluation of the proposed mechanism in a real world setting was undertaken and it showed that the proposed mechanism is highly robust and achieves better allocation efficiency than any fixed price system. A novel online mechanism in which agents representing vehicle owners are incentivized to be truthful not only about their marginal valuations for electricity units, but also about their arrival departure and maximum charging speeds is proposed in [51]. The authors extended the online mechanism proposed in previous paper [50] to also allow for modeling multi-unit demand per time step.

A decentralized smart charging strategy and V2G simulation for PHEVs within the large scale transport simulation framework MATSim was implemented in [52]. The charging decisions of all vehicles aim to reach a maximum load flattening effect. The charging algorithm relies on linear programming to optimize the charging durations for each parking interval. In [53], a decentralized charging control algorithm which is an application of Nash certainty equivalence for large population of PHEVs is developed to achieve social optimality by establishing a PHEV charging schedule that fills the overnight demand valley. This work shows that the control strategy results in valley filling under certain

reasonable conditions. Results show that if PHEVs act to minimize their cost with no regard of other PHEVs, the iterative scheduling process is unlikely to be convergent, but by penalizing for deviating from the average behavior of all other PHEVs the scheduling process is guaranteed to converge to the Nash equilibrium.

2.5. Optimal battery charging operation

The PHEV battery life and degradation are sensitive to the manner and time of charging. The charge trajectory of a PHEV is defined as the timing and rate with which the PHEV obtains electricity from the power grid in [54], and charging strategy should not too far from the optimal charging trajectory for greater battery life. In this paper, a multi-objective optimization algorithm based on the Non-Dominated Sorting Genetic Algorithm (NSGA-II) is considered for optimization of two objectives, (i) minimization of the total cost of fuel and electricity consumed by the PHEV over a 24 h naturalistic driving cycle, (ii) minimization of the total battery health degradation over a 24 h cycle. The comparisons of different solutions from the Pareto front includes that to effectively minimize battery degradation and energy costs a delayed charging strategy must be used.

A genetic optimization algorithm is applied in [55] to optimize the charging behavior of PHEV connected to grid with respect to maximizing the energy trading profit in V2G context and minimizing the battery aging costs. Simulation results show that proposed algorithm increases the battery life time drastically therefore reduces the mobility cost for the vehicle owner. Using a BPSO method an optimal charging profile for a Li-ion battery model is computed in [56]. This optimized charging profile is then used to map the State of Charge (SOC) against V2G transactions. Regulation Market Clearing Price (RMCP) data has been obtained from the Pennsylvania New Jersey Maryland Interconnections (PJM) website. BPSO lead to the least amount of battery degradation. Future studies include utilization of stochastic programming to account for uncertain nature of aggregated loads with an objective to improve SOC.

A summary of different research problems associated with charging techniques of PHEVs are presented in Table 2.

3. Renewable energy integration

3.1. Unidirectional operation

Unidirectional operation, as discussed before, corresponds to one way charging of PHEVs, in which the PHEVs cannot supply their stored energy to the grid. By suitably controlling the charging rate and the number of PHEVs being charged, the intermittent Renewable Energy Resources (RESs) can be integrated efficiently to the power grid. Such a problem is addressed in [57], which considers the problem of coordinated charging of PHEVs in an optimization framework, with the objective of maximizing the share of RESs and charging cost minimization, separately. The energy production from RESs, transportation requirements and electricity purchase price in the market are considered as random variables. The charging is undertaken in a centralized fashion, with clustering of PHEVs having similar driving patterns, instead of considering individual driving patterns for each PHEV separately. The results show higher charging cost, while maximizing share of RESs for charging, thereby highlighting the trade-off between cleaner and cost-effective operation.

An optimization framework is proposed in [58] to minimize the abandoned wind energy of the power system, using PHEVs. An empirical simulation study on a 9-bus system shows the peak load reduction and greater wind power integration with higher penetration

Table 2
Charging and scheduling of PHEVs.

Sl. no	Operating modes	Studied problem	Solution approach	References
1.	Unidirectional operation	(a) Coordinated charging of PHEVs	RT-SLM, Optimization based frameworks, optimal charging algorithms	[24–26,28]
		(b) Functions of electric vehicle charging provider	Optimization based technique	[27]
2.	Vehicle-to-grid operation	(a) Scheduling of charge/discharge times of PHEVs and effects of grid faults on V2G	Binary Particle Swarm Optimization (BPSO)	[29]
		(b) Control of both charging/discharging of PHEVs in V2G mode for meeting peak demand voltage reduction, reduction of charging costs, minimization of charging time, maximization of profits etc.	Linear and quadratic approximation model, fuzzy based controllers, BPSO, discrete and continuous PSO, dynamic programming, optimal algorithms, Q-learning algorithm, Markov chain	[30–35, 37–40, 42,43]
		(c) Utilization of PHEV parking lot to provide both active and reactive power	A real time current controlled PHEV parking lot	[36]
		(d) Impact of PHEVs on power quality of the smart grid for different battery charging rates	MATLAB, Decoupled harmonic power flow	[41]
3.	Charging control in the grid	(a) PHEV charging schedule	Joint OPF-charging optimization	[44]
		(b) Illustration of trade-offs that distribution network operators might encounter when implementing various load control approaches of electric vehicles	TCOPF	[45]
		(c) Utilization of excess distribution capacity	Queuing theory, statistical analysis	[46]
		(d) EV recharger allocation	Voronoi diagram, priority order circular diagram	[47]
		(e) Integration of electric vehicles through unbundled smart metering and virtual power plant (VPP) technology in the smart grid	Smart meter unbundled architecture	[48]
		(f) Implementation of V2G concept	Multilayer framework, PSO	[49]
4.	Online mechanism and game theoretic models	(a) Coordination of PHEVs charging schedule	Online mechanisms, decentralized smart charging strategy, MATsim, Nash certainty equivalence	[50–53]
5.	Optimal battery charging operation	(a) Minimization of PHEVs battery degradation	NSGA-II, BPSO	[54,56]
		(b) Maximization of energy trading profits and minimization of PHEVs battery aging costs	Genetic algorithm	[55]

of PHEVs. In [59], unidirectional PHEV charging strategies are evaluated for their performance in reducing peak load in presence of wind power and demand response programs. Different vehicle types and driving patterns are included in the simulation and a unit commitment model is applied to optimally schedule the PHEV charging in presence of load shifting by demand response programs. A sliding mode control strategy using the real-time demand supply imbalance signal to control the charge rate of all connected PHEV to reduce such imbalance is illustrated in [60]. This simple centralized strategy based on grid broadcast signal is shown to be robust with respect to uncertainties in number of PHEVs connected and renewable energy generation.

3.2. Vehicle-to-grid model

Along with the unidirectional charging of PHEVs, V2G models have been investigated for renewable energy integration applications. In this setting, bidirectional electric power flow or in other words both charging and discharging of PHEVs are taken into account. In related studies [61,62], the future smart grid is modeled as a cyber-physical energy system, with renewable energy resources and PHEVs. In such an environment, a mixed PSO technique is proposed to minimize the fuel cost, start-up cost and emission with a single weighted objective function. The algorithm uses binary Particle Swarm Optimization (PSO) for unit commitment solutions of conventional fuel-based power plants, integer PSO for determining the required number of PHEVs for participation in the V2G program and continuous PSO for deciding the output of RESs. In this centralized approach, the PHEVs in the system are assumed to be homogeneous and used in the V2G mode to aid in maximum utilization of the RESs (in this case solar and wind). This highlights the importance of capital investment in deploying more RESs to provide the additional power requirement created by the PHEV fleet. In [63], an aggregate of PHEVs is shown to level the output of wind power plant, with adequate size of the PHEV fleet. Results indicate little correlation between individual vehicle owner preferences and grid level performance. However, when wind power is low for longer than usual time, the PHEV fleet might be insufficient in providing desired fluctuation balancing performance. The conception and benefits of wind-electric vehicle complementation are presented in [64] from point of view of a transmission grid. A mathematical model on charging and discharging charging in aggregator mode is simulated. IEEE 9 bus system is considered for system model. Results show that the abandoned wind energy becomes less when PHEV penetration is higher in bidirectional coordinated mode than the unidirectional coordinated charging mode. In [65], a Probabilistic Constrained Load Flow (PCLF) problem is formulated in the context of a smart grid, modeling the output of wind energy system. Electric vehicle charging and discharging is modeled using queuing theory. The solution to the PCLF is obtained using a hybrid learning automata system, which can tackle both discrete and continuous variables. This iterative method is argued to have several advantages over heuristic optimization techniques and Monte-Carlo simulation techniques. The simulation results were obtained on 14-bus test system, with two wind generation plants and PHEV charging stations and correlated integration of PHEV and wind to the power system.

3.3. Case studies

In this section, we survey a number of real world implementation projects which try to integrate wind energy production into the smart grid with the help of PHEVs to reduce their intermittent production. Denmark is one of the largest producers of Wind power in the world and several case studies in this context have been carried for the Danish electricity market. Denmark has more wind generation compared to the balancing support and also has a high concentration of combined heat and power plants. In [66], the effectiveness of PHEVs under the V2G program to successfully integrate large scale wind energy systems and Combined Heat and Power (CHP) units into the power system is evaluated, for different wind penetration levels and intelligent charging strategies. Results indicate that PHEVs can help minimize excess wind production and CO2 emissions. In a similar study [67], futuristic scenarios are analyzed for 2025 and 2050 in Denmark, with similar charging strategies as in [66] including driving patterns. While the V2G smart charging strategy reduced the excess wind production and helped in better integration of wind power, it highlights the need for additional power production capacity for mismatch reduction in long term. Requirement of smart charging and V2G are highlighted, without which emission might increase in a power plant model with wind and thermal energy sources, resembling the Western Denmark market in [68]. In [69], a case study on PHEV penetration in the Danish power system is carried out, with a wind energy penetration close to 20%.

A study on a futuristic scenario in the Brazilian energy sector is carried out for successful integration of the planned expansion of the wind energy farms in [70]. The paper evaluates the possibility of using a Government controlled PHEV fleet to ensure efficient integration of the variable power output of the wind farm. The formulated optimization problem to minimize the cost of the proposed expansion is solved using the MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) tool [71]. The results indicate reduction of wind energy prices by the PHEV fleet by increasing the capacity factor of wind power plants and by reducing the costs of back-up capacity and storage energy, which would be required without the PHEV fleet. To determine the optimal number of PHEVs required for balancing the variability of wind power, a V2G aggregator model is proposed in [72] and is validated with actual wind output data from Sotavento wind firm in Spain.

A study is conducted for a futuristic German electricity market [73] with the objective of evaluating the impact of PHEVs for wind integration. Vehicle mobility behavior is modeled probabilistically, and vehicle charging is modeled indirectly using cost minimization function of market price and wind output. Depending on the price signals and mobility behavior, PHEVs calculate a cost minimizing charging schedule and therefore balance the fluctuation of wind power and peak load reduction. Several other studies for the German market are included on the wholesale market. In [74], wind imbalance of a large wind power plant (11 GW in North-West Power Pool in USA) is translated into a variation in frequency using a simple linear factor. The ability of a PHEV population reflecting actual driving patterns to meet the imbalance signal is studied in a unidirectional decentralized and uncoordinated charging framework. It only depends on the frequency variation and meeting the driving requirement. Impacts of different penetration levels of PHEVs on wind power balancing are compared. A short term power system operation model is presented in [75] where the electric vehicle management is considered. To determine the optimal system operation, the model resorts to a mixed integer programming problem. Contribution of electric vehicles on the integration of renewable energy sources is also determined. For the mainland Spanish electric system different PHEV penetration scenarios and power reserve provision are evaluated.

3.4. Unconventional approaches

An integrated power hub for a residential consumer, with capability of operating in both grid connected and island mode is presented in [76]. It had in built demand response capability in presence of renewable energy resources and PHEV. The PHEV

operates in a four quadrant mode and is crucial for island operation. In [77], the application of different vehicle types (Battery, PHEV and fuel cell) in V2G paradigm to provide backup and storage requirements of large offshore wind power plant is investigated. The required penetration level of different vehicle types to meet the requirement of regulation services, long wind shortfall periods, etc. are calculated in a numerical case study, considering a hypothetical scenario where 50% of energy in the USA is supplied from wind. In [78], a converter topology is developed to enable a Multi-Level Interlaced Pulse Charging (MLIPC) technique for old PHEV batteries (aged due to multiple cycles of charging and discharging). Under this scheme, packs of old and aged batteries can be efficiently charged and discharged and used as storage devices for RESs. The applicability of PHEVs for representation as a potential storage to offer additional balancing power is investigated in [79]. PHEV storage management approaches are based on a heuristic and a model predictive control scheme. Both schemes are compared and it is shown that heuristic method is scalable while both schemes are able to balance the forecast the error of renewable sources, such as wind to an acceptable level.

Different challenges associated with integration of renewable energy into the smart grid with the help of PHEVs are illustrated in Table 3 following the discussion in the literature.

4. PHEV participation in electricity markets

4.1. Agent-based models

PHEVs in the power grid can be modeled as a multi-agent system. In such a model, each PHEV will represent a self-interested and autonomous entity, and the goal of the system designer is to develop appropriate incentive mechanism to align the selfish behavior of the agents to result in a desire outcome for the overall system. In this case, PHEVs can be thought of trying to schedule their charging and discharging to minimize electricity purchase cost, while system operator coming up with appropriate pricing mechanism to ensure peak load reduction for the overall system. In many cases, tools from game theory are useful in analyzing such systems. In this section, we review the literature which model PHEVs in an agent-based framework.

For the utilization of PHEVs as primary reserve, a decentralized multi-agent System (MAS) is proposed in [80]. Simulations carried out on a fleet of PHEVs of a distribution grid show that the proposed model is able to control PHEVs as primary reserve and flatten the transformer load. To allow cooperation, negotiation and trading mechanisms within the elements of the network, an aggregative architecture for V2G communications that integrates MAS is proposed in [81]. The proposed architecture ensures robust V2G communications, while bringing added value of MAS mechanisms. In [82], MAS-based approach is employed to integrate PHEVs into the electricity grid managed by Pennsylvania New Jersey Maryland Interconnections (PJM) ISO to provide regulation services. System test results with five PHEVs show that PHEV owners can get substantial profits by participating in regulation market. The problem of generating multi agent coalitions for a group of PHEVs that participate in frequency regulation is explored in [83]. Coalition problem is modeled and various coalition formation strategies are proposed. Simulations based on a real world regulation signal, a realistic PHEV model and conventional gasoline drivers are used to evaluate the performance of proposed strategies.

An agent-based model of German electricity wholesale market with its four utility companies is presented in [84]. A heuristic reinforcement learning approach combined with genetic algorithm is used to develop bidding strategies for PHEV agents to increase their profits. Simulation results show the reduction of spot price volatility with PHEV integration. In a related work, a model predictive bidding [85] is proposed to choose bidding curves for the upcoming day, which are sent to the spot market. Results show that aggregating PHEVs to a cluster results in efficient operations of nuclear, hard coal and ignite power plants. PHEV cluster results in less market power compared to storage devices and more favorable market output. A game theoretic Cournot-model is used to analyze the impacts of hypothetical fleet of PHEVs on imperfectly competitive Germany electricity market in [86]. It investigates the combined decisions of oligopolistic generating firms on generation, vehicle loading and storage. Results depend on the player being in-charge of storage operation and degradation costs. In [87], a game-theoretic model is proposed to understand the interactions among PHEVs and aggregators where PHEVs participate in frequency regulation service. A smart pricing policy and a distributed mechanism to achieve optimal frequency regulation performance are developed. Simulation results show the efficacy of the proposed pricing mechanism in obtaining additional benefit for the PHEV owners and frequency regulation for grid.

4.2. Optimization-based models

The role of a PHEV aggregator in an electricity market is defined and characterized on a conceptual basis in [88], which can be used to design new markets and rules to utilize PHEVs as a flexible load or generation. Ideas proposed here are feasible with current Information and Communication Technology (ICT). An optimal control strategy for the aggregator that performs regulation service is developed in [89] using regulation price and charging cost as performance criterion. A dynamic programming technique is developed for the proposed

Table 3
Application in reducing intermittence of renewable energy production.

Sl. no	Operating modes	Studied problem	Solution approach	References
1.	Unidirectional operation	(a) Control of charging rate of PHEVs to aid in integration of wind and other intermittent renewable energy resources	Optimization based frameworks, sliding mode control strategies	[57–60]
		(b) Case studies on German and Spanish electricity markets	Optimization based methods	[72–75]
2.	Vehicle-to-grid model	(a) Control of both charging and discharging rate of PHEVs for renewable energy integration applications	Mixed PSO, BPSO, integer PSO, PCLF, queuing theory, hybrid learning automata system	[61–65]
		(b) Case studies on Danish electricity market on effectiveness of V2G	Different methods, mostly using market data	[66–69]
3.	Unconventional approaches	(a) Integrated power hub for a residential consumer	Lab VIEW , FPGA	[76]
		(b) Application of Battery, PHEV and fuel cell vehicle types in V2G paradigm	Based on the existing literatures of storage technologies	[77]
		(c) Charging of old PHEV batteries	MLIPC	[78]
		(d) Applicability of PHEVs to provide additional balancing power	Heuristic control scheme, model predictive control scheme.	[79]
		(e) Case study on Brazilian electricity sector	MESSAGE Tool	[70–71]

system. Using market price in the clearing of energy and reserves, an optimal bidding strategy of a load aggregator for battery charging is formulated in [90] as the solution to a stochastic dynamic programming. Results show that the proposed method lowers PHEV charging costs, mitigates local distribution network congestion constraints, increases system wide supply of regulation service and contributes efficient expansion of intermittent clean energy. For a PHEV aggregation agent, participation in day ahead and secondary reserve markets is formulated as an optimization problem in [91,92], to minimize the operational costs and increase profit margin. The model was used to evaluate the effectiveness of different price forecasting algorithms on cost minimization. The results show superior performance of advanced forecasting algorithms over uncontrolled/uncoordinated charging. Participation in secondary downward reserve market is shown to be economically attractive. Utilization of PHEVs as active power balancing reserve in Denmark is analyzed in [93] with large size wind power plant. Some worst case scenarios like coincident demand and wind ramp periods, days with high and low wind, reduced power balancing reserves, loss of generation are studied in case studies. Simulation results show robust and fast power system frequency regulation than conventional generators in providing active power balancing. To coordinate charging/discharging of PHEVs a stochastic linear programming optimization algorithm is proposed in [94] to minimize the charging costs. It is focused on day-ahead market and provides system regulation in ancillary market. Monte Carlo simulation is applied due to stochastic nature of transport model uncertainties.

4.3. Customer perspective

Existing research regarding conditions for potential use of batteries as power regulator are reviewed in [95]. The authors analyze the customer perspective of the PHEV role on the electricity market considering participation in control power market. The technical background required to construct a model that quantitatively simulates the electric vehicle customer in an electric system are discussed. An aggregator-based service provider is conceptualized in [96] to simultaneously achieve different user-specific or grid-specific charging schedules for a fleet of PHEVs. The charging services are transformed into objectives and constraints in a charging-scheduling problem and the cost effectiveness of different services are discussed.

4.4. Vehicle-to-grid

A mathematical model to estimate electric power capacity of a V2G parking lot system is developed in [97], with vehicles at different State Of Charge (SOCs) and arriving at different times for charging/discharging. The proposed model was tested on the Telsa Roadster Electric Vehicle (EV) and PHEV versions. Results show that V2G for peak load and regulation services has more economic value than other ancillary services. Some reference architectures for the control markets which control a large number of vehicles in Sweden and Germany with a predefined method are derived in [98]. It is shown that PHEVs can provide symmetric control power in two ways, either part generation or part controllable load. The results show that the systems require intelligence both in PHEVs and at charging points for part generation, while for part controllable load, PHEV intelligence is sufficient. A coordinating unidirectional V2G services with energy trading for a Load Serving Entity (LSE) is proposed in [99]. The LSE owns several thermal and wind power plants and a number of electric vehicles. Problem of coordinating V2G services with wind and thermal power plants is formulated as mixed integer stochastic linear program, with the objective to maximize LSE profit while maintaining its risk level below acceptable levels. Simulation results show increases in the expected profits for LSE, while improving risk and reducing emissions. The effect of driving efficiencies on optimal V2G bidding is explored in [100] using three optimal preferred operating point algorithms. V2G benefits and impacts on driving efficiencies are compared with calculated real world values for the Puget Sound region of Washington State. Results show that the amount of energy needed to charge the battery increase by 25%, the average and peak load increases by 20% for all the algorithms when real driving efficiencies are used. A practical demonstration of V2G power providing real-time frequency regulation from a electric car is explained in [101]. In the deregulated electricity markets, regulation can have an average value of $30-$40/MW per hour, while costliest among all being ancillary services. A second market of interest is spinning reserves with the values in the range $10/MW per hour but much less frequent dispatch.

4.5. Unit commitment

Scheduling problem of PHEVs is formulated as a Unit Commitment (UC) problem and is solved in conjunction with conventional power plants for cost minimization. Heuristic optimization techniques, such as PSO are employed to solve the constrained optimization problems. In [102], binary PSO is used for scheduling the power units whereas integer PSO is used for scheduling the vehicles. In a related work [103], a special case of a restricted parking slot is considered within which the scheduling of PHEVs is carried out. A follow-up work [104] includes the uncertainties in solar, wind energy sources and load in the cost and emission minimization problem. Output of RESs is determined by probabilistic estimation and PSO algorithm is used to determine the use of PHEVs as source, load or storage under different conditions. A hybrid of PSO and Ant colony Optimization (ACO) algorithms is developed in [105] to optimally charge and discharge PHEVs to solve the UC problem and improve reliability. This is also shown to reduce operational costs. In [106], a binary PSO technique is proposed for scheduling of PHEVs in order to achieve maximum profit. Power output and profits are compared when PHEVs charge/discharge only once a day or multiple times a day. Their dependencies of battery SOC are investigated Table 4.

An overview of different problems is listed in Table 5, that is used to address the subject of PHEV participation in electricity markets

5. Infrastructure facilities

5.1. Availability estimation and optimal deployment

For participation in different V2G programs or in the electricity market, it is often required to correctly estimate the available power at different locations and at different times in a day. This is typically done by tools from probability theory and/or using data of vehicle usage pattern. A stochastic model based on non-homogeneous semi Markov process is developed to address the above problem in [107]. German traffic study *Mobilitat in Deutschland* 2008 is taken as a database for modeling purposes and classifies the PHEVs into different states, to estimate the probability of a vehicle to be in a given state and the duration it occupies in that state. The proposed method can be easily adaptable to different sets of data. Estimation of available storage capacity for participation in V2G program is carried out in [108] by using Monte-Carlo simulation on driving profiles. Driving profiles are generated using vehicle usage data from an extensive survey. Effect of different levels of PHEV penetration on load and availability of PHEVs are studied. Results show investment in home charging infrastructure to be the most beneficial. Requirement of intelligent charging strategies were also

Table 4
Phev participation in electricity markets.

Sl. no	Operating modes	Studied problem	Solution approach	References
1.	Agent-based and game theoretic models	(a) PHEVs as primary reserve	Decentralized MAS, aggregative architecture, game theoretic Cournot-model, agent-based model	[80–81]
		(b) PHEVs as regulation service providers	MAS, coalition formation strategies, game theoretic models	[82,83,87]
		(c) Bidding strategies for PHEV agents	Heuristic reinforcement learning approach combined with genetic algorithm, model predictive bidding	[84,85]
		(d) Impacts of PHEVs on imperfectly competitive Germany electricity market	Game theoretic Cournot-model	[86]
2.	Optimization-based models	(a) PHEV aggregator role in electricity market	Conceptual basis	[88]
		(b) Control strategy for aggregator performing frequency regulation	Optimal control strategy, dynamic programming technique	[89]
		(c) Strategy for load aggregator for battery charging	Optimal bidding strategy, stochastic programming strategy	[90]
		(d) Aggregator in day ahead and secondary reserve market	Optimization based techniques	[91–92]
		(e) Utilization of PHEVs as active power balancing	Stochastic linear programming	[93]
		(f) Coordination of charging/discharging of PHEVs	Stochastic linear programming, Monte Carlo simulation	[94]
3.	Consumer perspective	(a) Customer perspective of the PHEV role on the electricity market	Conceptual basis	[95]
		(b) Charging scheduling for a fleet of PHEVs	Aggregator based model	[96]
4.	Vehicle-to-grid	(a) Estimation of electric power capacity of a V2G parking lot	Battery modeling	[97]
		(b) Reference architecture for control markets to control a large number of vehicles	Different requirement domains like delimitations, control market constraints	[98]
		(c) Coordination of V2G unidirectional services	Mixed integer stochastic linear program	[99]
		(d) Effect of driving efficiencies on optimal V2G bidding	Optimal preferred operating point algorithms	[100]
		(e) Utilization of V2G power for real time frequency regulation	Practical demonstration	[101]
5.	Unit commitment	(a) Scheduling of PHEVs for charging/discharging	PSO, integer PSO, probabilistic estimation, BPSO, hybrid of PSO and ACO	[102–106]

Table 5
Infrastructure facilities.

Sl. no	Operating modes	Studied problem	Solution approach	References
1.	Availability estimation and optimal deployment	(a) Estimation of available power for participation in V2G program	Non-homogeneous semi Markov process, Monte-Carlo simulation	[107–108]
		(b) Comparison between coordinated and uncoordinated charging strategies	Optimization based techniques	[109]
2.	Parking area	(a) Use of PHEVs parking lots as shock observers and to prevent overload of transmission lines	Real time digital simulator	[110]
		(b) Control of charging/discharging of PHEVs and pitch angle for wind power	Fuzzy based controllers	[111]
		(c) Charging time of PHEVs	Smart energy management system	[112]
		(d) Control of PHEVs charging	Optimization based techniques	[113–117]
		(e) Benefits of PHEVs and BEVs for energy management	Optimization based techniques	[114]
		(f) Power and communication networks for the smart grid	Real time simulation, SITL, HILS	[115]
		(g) Use of PHEVs parking lot as STATCOM	Real time digital simulator	[116]

highlighted. The model could be extended to the future driving behavior patterns and different intelligent charging strategies.

A comparative study is undertaken between coordinated and uncoordinated charging strategies in [109]. In the uncoordinated approach, the main objective is to reduce the cost of operation for the PHEV owner. In the coordinated approach, minimization of distribution loss and maximization of distribution load factor are considered separately. Impact of different PHEV penetration levels on load profiles and power losses are compared. The results highlight the relative trade-offs between different objectives.

5.2. Parking area

Large parking lots provide an opportunity to control a fleet of PHEVs in an intelligent manner. Possible use of PHEVs in parking lots to prevent the transmission lines getting overloaded and to act as shock observers when the wind power changes drastically is explored in [110]. A fuzzy-logic controller is proposed in [111] which takes the total state of charge of a parking lot, instantaneous demand and wind power generated as inputs and gives control signals for charging/discharging of the PHEVs. Simulations on a 12 bus system model show that when PHEVs charge and discharge according to the control signal, overloading of the transmission lines during high wind speeds can be prevented and the fluctuations in wind power supply to the grid can be reduced. A smart energy management system is proposed in [112] which significantly reduces the charging time of PHEVs in fast a charging station by the use of additional flywheel and super capacitors. The results for two PHEV batteries between 10 kW h and 15 kW h show the charging time is 15 min on average to charge from a

Table 6
Advantages of selected publications.

Serial no.	Reference	Problem	Solution approach and advantages
1.	[26]	Coordinated charging of PHEVs	Convex optimization formulations for loss minimization, load factor maximization, and load variance minimization. Efficient solution methods for large problem instances
2.	[27]	Centralized charging of PHEVs in presence of distribution grid constraints	Detailed model of different market entities, including distribution system operator, retailor and PHEV charging controller and their interactions
3.	[50]	Distributed charging mechanism	Online auction-based mechanism. Greedy allocation rule achieves truthful behaviour in players
4.	[65]	Wind energy integration	Hybrid learning automata system for solving probabilistically constraint load flow problem
5.	[73]	Balancing fluctuations of wind power generations	Model predictive control approach validated with real wind generation data
6.	[92]	PHEV aggregator bidding strategy	Day-ahead market and reserve market bidding strategy is developed for PHEV aggregator agent
7.	[99]	Short-term power market uncertainty mitigation	V2G to mitigate trading risk due to uncertainty in short-term market
8.	[113]	Smart parking	Architecture of a smart parking lot with detailed communication, control, pricing models

minimum SOC 20% to 95% in the new configuration. The proposed model in [113] allocates the power to the available PHEVs to ensure the optimal usage of available power, charging time and grid stability in real-time. Customer preference, load conditions, battery model and state-of-charge are taken into account. The benefits of PHEVs and BEVs as energy storage for demand side management and outage management are discussed in [114], in the light of providing power to buildings and home. Simulation studies on the IEEE 37 node radial test feeder under a cost-minimization framework show that PHEVs supply more power to the buildings during peak load and fault conditions providing cost reduction and restoration, respectively. In [115], Hardware-in-Loop simulation platform is developed for both continuous (power electronics and power systems) and discrete (communication networks) parameters. PHEV load management, islanding and load dynamics are studied considering different aspects of the communication network, such as delays, bandwidth, etc.

Possible use of a PHEV fleet in a parking facility as a Static Synchronous Compensator (STATCOM) is explored in [116]. The work focuses on two different applications of STATCOM, 1) Providing voltage regulation and 2) Reactive power control for wind farms. Performance of the PHEV fleet is compared with an actual STATCOM in real-time, and is shown to improve voltage control and fault ride through performance. Optimal sizing of the Local Energy Storage (LES) for charging facility is developed in a cost-minimization framework in [117]. Appropriate control strategies for proper integration of LES with PHEV charging stations are developed. The results show that system with the optimized parameters operates well during the grid-connected and islanding modes and also during the transient period with reduced voltage and current spiking.

Table 5 demonstrates a summary of different problems addressed and the corresponding solution techniques discussed in this section.

6. Conclusion

In this paper, recent research literature in four broad domains of PHEV integration in smart grid is surveyed. Some of the domains such as electricity market participation of PHEVs and smart parking lot design had previously received little attention in the review paper literature. The focus of this paper has been in computational and algorithmic aspects of the research. To highlight some of the more advantageous solution methodologies, we discuss a selected set of publications in Table 6 in each of the problem domains.

Large scale adaptation of PHEVs is not only critical to the goal of a sustainable and carbon free transportation sector, but also to the success of smart grid and renewable energy integration. An extensive review of several critical research problems and challenges in conceptualization, implementation and application aspects of PHEVs are presented here. PHEVs are crucial for the next generation power grid, and future research in this area is likely to grow in future in different interesting directions.

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